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Uncertainty in positioning ion chamber at reference depth for various water phantoms

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ABSTRACT

Background: Uncertainty in the calibration of high-energy radiation sources is dependent on user and equipment type.
Aim: We evaluated the uncertainty in the positioning of a cylindrical chamber at a reference depth for reference dosimetry of high-energy photon beams and the resulting uncertainty in the chamber readings for 6- and 10-MV photon beams. The aim was to investigate major contributions to the positioning uncertainty to reduce the uncertainty in calibration for external photon beam radiotherapy.
Materials and methods: The following phantoms were used: DoseView 1D, WP1D, 1D SCANNER, and QWP-07 as one-dimensional (1D) phantoms for a vertical-beam geometry; GRI-7632 as a phantom for a fixed waterproofing sleeve; and PTW type 41023 and QWP-04 as 1D phantoms for a horizontal-beam geometry. The uncertainties were analyzed as per the Guide to the Expression of Uncertainty in Measurement.
Results: The positioning and resultant uncertainties in chamber readings ranged from 0.22 to 0.35 mm and 0.12–0.25%, respectively, among the phantoms (using a coverage factor $k = 1$ in both cases). The major contributions to positioning uncertainty are: definition of the origin for phantoms among users for the 1D phantoms for a vertical-beam geometry, water level adjustment among users for the phantom for a fixed waterproofing sleeve, phantom window deformation, and non-water material of the window for the 1D phantoms for a horizontal-beam geometry.
Conclusion: The positioning and resultant uncertainties in chamber readings exhibited minor differences among the seven phantoms. The major components of these uncertainties differed among the phantom types investigated.

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1. Background

Calibration for external beam radiation therapy is performed with ionization chambers calibrated in absorbed dose-to-water standards.[1–3] Ionization chambers are commonly calibrated by primary standards dosimetry laboratories or secondary standards dosimetry laboratories in terms of the absorbed dose to water in a cobalt-60 beam. Currently, several standards laboratories offer direct calibration services.[4,5] An addendum to AAPM's TG-51 provided new data on the beam quality conversion factor k_Q for photon beams based on Monte Carlo calculations.[6,7] Because the uncertainty in the absorbed dose calibration coefficient obtained from direct megavoltage calibration or the new k_Q values would be small, most of the uncertainty in the determination of the absorbed dose-to-water at a reference depth may depend on the users' methods and equipment.

Today, users can choose from various water phantoms. Because users' settings and the inherent characteristics among phantoms differ, the positioning uncertainty could change. Although some reports have described the measurement uncertainty, to our knowledge, the uncertainties associated with various types of equipment have not been discussed in detail.[8–11]

2. Aim

We assessed the uncertainties in the positioning of an ion chamber at the reference depth of clinical reference dosimetry for seven phantoms and the resulting uncertainties in the chamber readings. The aim was to investigate the major contributions to the positioning uncertainties for the seven phantoms to reduce the measurement uncertainty.

3. Materials and methods

3.1. *Overview*

This work focused on the uncertainty in the positioning of an ion chamber at the reference depth of 10 g/cm^2 for clinical reference dosimetry of high-energy photon beams and the resulting uncertainties in the chamber readings for 6- and 10-MV photon beams. Because radiation doses in megavoltage photon beams are best measured with Farmer-type chambers, a PTW 30013 chamber (PTW, Freiburg, Germany) was selected to evaluate the positioning uncertainty. The photon beams were generated by a Siemens Artiste linear accelerator (Siemens AG, Erlangen, Germany). Furthermore, we verified the validity of the estimated reading uncertainties.

3.2. *Phantoms investigated*

Tables 1 and 2 summarize both the characteristics of the phantoms investigated and the procedures. The five phantoms were used for a vertical-beam geometry: DoseView 1D (Standard Imaging, Middleton, WI), WP1D (IBA Dosimetry, Schwarzenbruck, Germany), 1D SCANNER (Sun Nuclear, Melbourne, FL), QWP-07 (Qualita, Nagano, Japan), and GRI-7632 (Nichigen, Tokyo, Japan). The other two were used for a horizontal-beam geometry: PTW type 41023 (PTW, Frieburg, Germany) and QWP-04 (Qualita, Nagano, Japan).

3.3. *Uncertainty analysis*

The positioning uncertainties and the resulting uncertainties in the chamber readings were analyzed following the recommendations of the Guide to the Expression of Uncertainty in Measurement.[12] The limits of the variation in an estimated component could be accurately known while its distribution is unknown. In such cases, the components classified as type B were assumed to have a rectangular distribution. The reading uncertainties were estimated by the law of propagation of uncertainty. A coverage factor of $k = 1$ was assumed for every uncertainty, corresponding to a confidence limit of 68.3%.

3.3.1. *Uncertainty in the users' techniques*

Table 3 summarizes the techniques considered for the phantoms. Before the techniques were performed, all the tested phantoms were leveled after the water was poured. The origin for the QWP-04 phantom was determined by the contact between the inner surface of the phantom window and a distance calibration disk to set the origin.

The techniques were performed by nineteen operators; six junior-level, seven intermediate-level, and six senior-level operators at five facilities. Additionally, these techniques were repeated ten times by one of the operators to assess the uncertainties in their repeatability. The chamber positions that defined the origin for the five phantoms were read from the display of the chamber position. 10-cm adjustments of a caliper on the PTW 41023 phantom top for setting the chamber depth were assessed with an IL-300 laser distance meter (Mitutoyo Corporation, Kanagawa, Japan), whereas determinations of the water surface position for the GRI-7632 phantom were measured with a QWP-43 water-level indicator (Qualita, Nagano, Japan). The uncertainties in the equipment used for assessing these uncertainties were taken from their specifications and classified as type B.

3.3.2. *Uncertainty in the inherent characteristics of the phantom*

Table 4 summarizes the uncertainties in the inherent characteristics of the phantoms considered. All water phantoms have an uncertainty in the chamber depth as the temperature-induced water density changes. For the water temperature of approximately 24 °C used in this work, the water density was approximately 0.9972 g/cm^3. When the chamber was positioned at a depth of 10 cm from the surface, the real position was approximately 0.3 mm shallower. This uncertainty was assessed as type B. The movement distances from the origin to a depth of 10 cm were measured 10 times by using the IL-300 laser distance meter. The length of the analog scale for the PTW type 41023 and GRI-7632 phantoms was measured with a 30-cm ruler certified as Japanese Industrial Standards Grade 1. For the PTW type 41023 and GRI-7632 phantoms, the air gap between the chamber wall and the waterproofing sleeve was obtained from the manufacturer and user manuals.

Table 1 – Characteristics of the phantoms for a vertical-beam geometry.

Phantom	Wall material	Size (inner) $L \times W \times H$ (cm^3)	Measurement type	Procedure for positioning ionization chamber[a]
DoseView 1D	PMMA	$42 \times 40 \times 36$	One-dimensional water scanner	(1) D and (2) M
WP1D	PMMA	$40 \times 34 \times 35$	One-dimensional water scanner	(1) D and (2) M
1D SCANNER	PMMA	$35.0 \times 39.0 \times 36.2$	One-dimensional water scanner	(1) D and (2) M
QWP-07	PMMA	$42.4 \times 37.4 \times 38.7$	One-dimensional water scanner	(1) D and (2) M
GRI-7632	PMMA	$30 \times 30 \times 35$	Fixed waterproofing sleeves	(1) A

[a] D: definition of the origin at the water surface: positioning the center of the chamber at the surface, M: motorized adjustment of the measurement depth, A: adjustment of the water level by means of a vertical scale.

Table 2 – Characteristics of the phantoms for a horizontal-beam geometry.

Phantom	Wall material	Size (inner) $L \times W \times H$ (cm^3)	Window thickness (mm)	Measurement type	Procedure for positioning chamber
PTW type 41023	PMMA	$28 \times 28 \times 29$	3.05	One-dimensional water scanning	Manual adjustment of the measurement depth using a caliper on the phantom top
QWP-04	PMMA	$30 \times 26 \times 32$	3	One-dimensional water scanning	(1) Definition of the origin at a water-equivalent depth of 1.0 g/cm^2: positioning the center of the chamber at the 1.0 g/cm^2 depth, and (2) manual adjustment of the measurement depth

Table 3 – Uncertainty components in the users' techniques for the seven phantoms.

Phantom	Uncertainty type A	Uncertainty type B
DoseView 1D, WP1D, 1D SCANNER, and QWP-07	Repeatability of origin definition	(1) Definition of the origin among users, and (2) equipment used for the evaluation
GRI-7632	Repeatability of 10-cm adjustment of the water level	(1) 10-cm adjustment of the water level among users, and (2) equipment used for the evaluation
PTW type 41023	Repeatability of 10-cm adjustment of the caliper	(1) 10-cm adjustment of the caliper among users, and (2) equipment used for the evaluation
QWP-04	Repeatability of origin definition	(1) Definition of the origin among users, and (2) equipment used for the evaluation

Table 4 – Uncertainty components in the inherent characteristics of the seven phantoms.

Phantom	Uncertainty type A	Uncertainty type B[a]
DoseView 1D, WP1D, 1D SCANNER and QWP-07	Repeatability of the actual movement from the origin to a depth of 10 cm	(1) AM and (2) N
GRI-7632	–	(1) AS (2) AG, and (3) N
PTW type 41023	–	(1) D, (2) AS, and (3) N
QWP-04	Repeatability of the actual movement from the origin to a depth of 10 cm	(1) D, (2) AM, and (3) N

[a] AM: actual movement distance between the origin and the reference depth, N: nonapplied correction attributable to the water density, AS: analog scale, AG: air gap between the chamber wall and the waterproofing sleeve, D: phantom window deformation.

The entrance windows for a horizontal-beam geometry generally have an outward bowing due to the water pressure on the inner surface. This effect can change the chamber depth and source-to-surface distance (SSD). The deformation was monitored with an ID-S112SB dial indicator (Mitutoyo Corporation, Kanagawa, Japan), for 60 min after the phantoms were filled. Furthermore, we evaluated the uncertainty associated with the non-water material of the window by measurements; the chamber was set up at a water-equivalent depth of 10 g/cm^2 in a phantom for a vertical-beam geometry, with or without an entrance window, with the same dimensions (i.e., thickness and size) and the same material as the two phantoms used here. Then, the phantom was leveled after the water was poured; the field size was 10 cm × 10 cm at the chamber.

The uncertainties in the equipment used for assessing these uncertainties were taken from their specifications and classified as type B.

3.4. *Verification of the uncertainty in the chamber reading from the positioning uncertainty*

To verify the uncertainty in the chamber reading estimated in this work, we derived it from the distribution of the chamber readings under the reference conditions according to IAEA TRS-398. All the tested phantoms were leveled after the water was poured. The chamber was set up nineteen times by the nineteen operators over the course of these measurements, maintaining a constant source-axis distance and field size. The measurements were performed using the PTW 30013 chamber connected to a RAMTEC smart electrometer (Toyo Medic, Tokyo, Japan). The readings were corrected for temperature and pressure according to TRS-398.

4. Results

4.1. *Uncertainty analysis*

4.1.1. *Uncertainties in the users' techniques*

Fig. 1 shows the results of the users' techniques performed by the nineteen operators. The variations in the setting of the origin for the four phantoms for a vertical-beam geometry (Fig. 1(a–d)), the determination of the water surface for the GRI-7632 phantom (Fig. 1(e)), the 10-cm adjustment of the caliper (Fig. 1(f)) for the PTW type 41023 phantom, and the setting of the origin for the QWP-04 phantom (Fig. 1(g)) were 0.60–0.80 mm, 0.86 mm, 0.41 mm, and 0.55 mm, respectively. The variations in the water-level adjustment and the setting of the origin at the surface were larger than those obtained by the other techniques for a horizontal-beam geometry.

Table 5 summarizes the uncertainty budgets for the users' techniques. Their combined uncertainties for a vertical-beam geometry ranged from 0.19 mm to 0.26 mm, whereas those for a horizontal-beam geometry ranged from 0.13 mm to 0.17 mm. The major contribution to their uncertainties was attributable to the users' techniques performed by the nineteen operators. The uncertainty in the water-level adjustment was slightly larger than those for the other techniques.

4.1.2. *Uncertainties in the inherent characteristics of the phantoms*

Compared to the reference depth of 10 cm, the mean actual movement distance had the following errors: DoseView 1D, 0.09 mm; WP1D, 0.35 mm; 1D SCANNER, 0.11 mm; QWP-07, 0.10 mm; and QWP-04, 0.12 mm. The air gap between the chamber wall and the waterproofing sleeve was 0.1 mm for GRI-7632 and 0.21 mm for PTW type 41023. For the horizontal-beam geometry, the actual deformation was up to 0.506 mm and 0.359 mm for the PTW type 41023 and QWP-04 phantoms, respectively, for 60 min after the phantoms were filled (Fig. 2). Errors of the length of the analog 10-cm scale were as follows: approximately 0.24 mm and 0.09 mm for GRI-7632 and PTW type 41023, respectively.

Table 6 lists the uncertainty budgets for the inherent characteristics of the phantoms. The combined uncertainties for the seven phantom ranged from 0.12 mm to 0.28 mm. For the one-dimensional phantoms for a vertical-beam geometry except with WP1D, the uncertainty in the nonapplied correction attributable to the water density was 0.09 mm and somewhat larger than the other uncertainty components in the inherent characteristics of the phantoms. The largest uncertainty components in the inherent characteristics of the phantoms for the WP1D, GRI-7632, and PTW type 41023/QWP-04 phantoms were the mean movement distance from the origin to the 10-cm depth, the analog scale, and the window deformation, respectively, and the values of their uncertainties were 0.21 mm for WP1D, 0.19 mm for GRI-7632, and 0.11–0.15 mm for QWP-04 and PTW type 41023.

4.1.3. *Combined standard uncertainty*

Table 7 summarizes the combined positioning uncertainties for the seven phantoms. The positioning uncertainties ranged from 0.24 mm to 0.35 mm among the seven phantoms.

The largest components of the positioning uncertainties were the water-level adjustment performed by the operators, the window deformation, and the setting of the origin carried out by the operators for the GRI-7632, PTW type 41023, and QWP-04 phantoms, respectively (Tables 5 and 6). The main component of the uncertainty for the 1D phantoms for a vertical-beam geometry was the setting of the origin among the users, except for the WP1D phantom, for which the largest contribution to the positioning uncertainty was the movement distance from the origin to the 10 cm depth (Tables 5 and 6).

4.1.4. *Uncertainty in the chamber reading from the positioning uncertainty*

Table 8 presents the uncertainties in the chamber readings from the positioning uncertainties for the seven phantoms. The variations in the uncertainties in the readings for the five phantoms for a vertical-beam geometry were 0.14–0.20% for 6 MV and 0.12–0.16% for 10 MV. Given the uncertainty associated with the non-water material of the phantom, the uncertainties in the readings for a horizontal-beam geometry were 0.22–0.25% for 6 MV and 0.19–0.21% for 10 MV, which were slightly larger than those for a vertical-beam geometry.

4.2. *Verification of the uncertainty in the chamber reading from the positioning uncertainty*

Table 9 summarizes the uncertainties in the chamber readings for the phantoms deduced from the measurements. The uncertainties in the chamber readings ranged from 0.08% to 0.18% among the phantoms. Comparing Tables 8 and 9, the uncertainties in the chamber readings obtained from the measurements (Table 9) were smaller than the estimated uncertainties (Table 8).

5. Discussion

This work had four major findings. First, the positioning uncertainties and the resultant uncertainties in the chamber readings exhibited minor differences among the seven phantoms. Second, the users' techniques were different among the operators. Third, the uncertainty components in the inherent characteristics of the phantoms were slightly larger in the phantoms for a horizontal-beam geometry than in those for a vertical-beam geometry. Finally, each type of phantom,

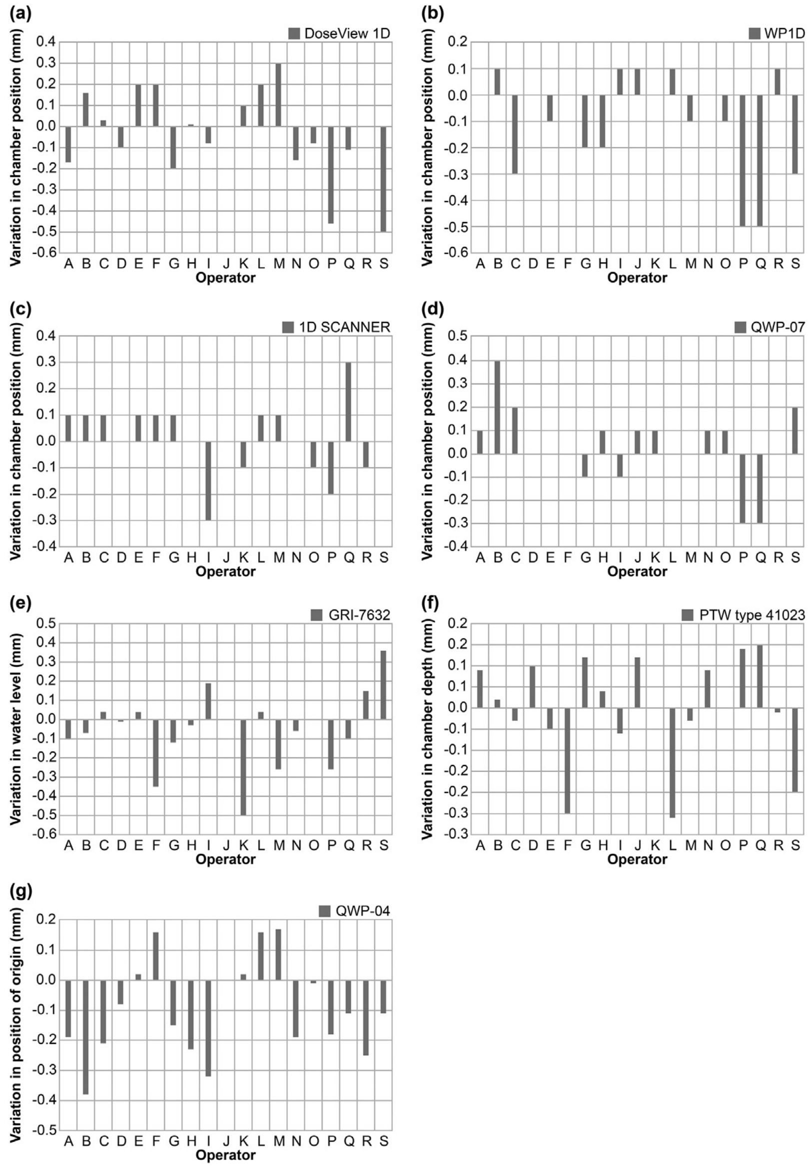

Fig. 1 – Variation in the users' techniques among the operators (each operator performed one measurement with each equipment type): A–F: senior level operators, G–M: intermediate level operators, and N–S: junior level operators. (a) DoseView 1D, (b) WP1D, (c) 1D SCANNER, (d) QWP-04, (e) GRI-7632, (f) PTW type 41023, (g) QWP-04. Negative values indicate that the chamber is deeper in (a)–(d) and (f), the water level is shallower in (e), and the position of the origin is deeper in (g).

Table 5 – Estimated standard uncertainties in the users' techniques and their components for the seven phantoms.

Source and type of uncertainty	DoseView 1D	WP1D	1D SCANNER	QWP-07	GRI-7632	PTW type 41023	QWP-04
	Setting the origin at the water surface				10-cm adjustment of the water level	10-cm adjustment of a caliper	Setting the origin at the depth of 1.0 g/cm^2
Technique among users (mm)	0.23	0.18	0.18	0.21	0.25	0.12	0.16
Standard deviation of the technique (mm) ($n = 10$)	0.02	0.06	0.02	0.03	0.02	0.02	0.02
Measurement instrument used for the determination of the uncertainty (mm)	0.003	0.03	0.03	0.03	0.06	0.03	0.03
Combined uncertainty (mm) ($k = 1$)	0.24	0.20	0.19	0.22	0.26	0.13	0.17

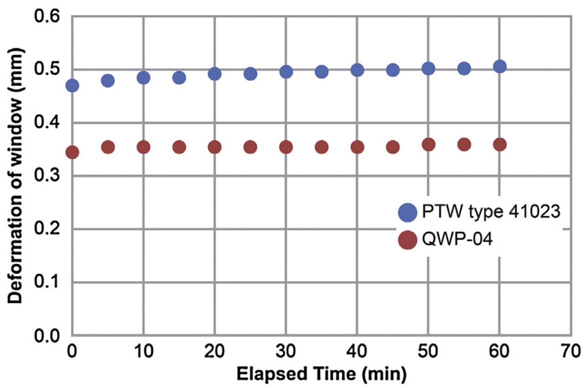

Fig. 2 – Behavior of the phantom window deformation for the 60 min immediately following the filling of the phantom. Each equipment type was used to take a single measurement.

namely, the 1D phantoms for a vertical-beam geometry, the phantom for a fixed waterproofing sleeve, and the 1D phantoms for a horizontal-beam geometry, had different major contributions to the positioning uncertainty.

The addendum to TG-51 states that a positioning uncertainty of 0.33 mm should be achievable without specialized equipment.[6] This uncertainty of 0.33 mm and the positioning uncertainties estimated here are similar within 0.10 mm. Therefore, our results suggest that the estimated uncertainties had minor differences among the seven systems, and the seven phantoms worked well for a mass-produced piece of equipment.

Our results indicate the following positioning uncertainties in detail in comparison with the addendum to TG-51: (1) the positioning uncertainties corresponding to the seven phantoms used, (2) the uncertainty budgets for the users' techniques and the inherent characteristics of the phantoms, and (3) the major contributions of the positioning uncertainty and the resulting uncertainties in the chamber readings. Therefore, our results could be helpful for reducing the measurement uncertainty.

Fig. 1 suggests that the users' techniques would be different among operators, especially for junior-level and intermediate-level operators. Therefore, it is important for a single user as well as a group of users to be trained with a consistent technique. Table 5 indicates that the uncertainties in the water-level adjustment among the users are slightly larger than the other ones. For the uncertainty in the water-level adjustment, a possible error originates from the visual error due to the surface-tension effect. Therefore, determination of a criterion for their technique, such as the simple optical method of Das et al. to set the origin at the water surface,[13] would be important for users.

Tables 6 and 8 indicate that the uncertainty components in the inherent characteristics of the phantoms for a horizontal-beam geometry were slightly larger than those of the five

Table 6 – Estimated standard uncertainties in the inherent characteristics of the seven phantoms and their components.

Source	Uncertainty (mm)						
	DoseView 1D	WP1D	1D SCANNER	QWP-07	GRI-7632	PTW type 41023	QWP-04
Movement distance from the origin to a depth of 10 cm (mm)	0.06	0.21	0.07	0.06	–	–	0.07
Standard deviation of the distance from the origin to a depth of 10 cm (mm) ($n = 10$)	0.006	0.01	0.01	0.02	–	–	0.05
Analog scale (mm)	–	–	–	–	0.19	0.14	–
Air gap between the chamber wall and the waterproofing sleeve (mm)	–	–	–	–	0.06	0.13	–
Phantom window deformation (mm)	–	–	–	–	–	0.15	0.11
Nonapplied correction attributable to the water density (mm)	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Measurement instrument used for determination of the uncertainty (mm)	0.03	0.03	0.03	0.03	0.08	0.09	0.03
Combined uncertainty (mm) ($k = 1$)	0.12	0.24	0.12	0.12	0.24	0.28	0.17

Table 7 – Combined standard uncertainties in the positioning of the chamber at the reference depth for the seven phantoms.

Source	Uncertainty (mm)						
	DoseView 1D	WP1D	1D SCANNER	QWP-07	GRI-7632	PTW type 41023	QWP-04
Users' techniques (mm)	0.24	0.20	0.19	0.22	0.26	0.13	0.17
Inherent characteristics of the phantoms (mm)	0.12	0.24	0.12	0.12	0.24	0.28	0.17
Combined uncertainty (mm) ($k = 1$)	0.26	0.30	0.22	0.25	0.35	0.30	0.24

Table 8 – Estimated relative standard uncertainties in the chamber readings for the seven phantoms.

Source	Uncertainty (%)													
	DoseView 1D		WP1D		1D SCANNER		QWP-07		GRI-7632		PTW type 41023		QWP-04	
	6 MV	10 MV	6 MV	10 MV	6 MV	10 MV	6 MV	10 MV	6 MV	10 MV	6 MV	10 MV	6 MV	10 MV
Positioning the chamber at the reference depth	0.17	0.14	0.20	0.17	0.16	0.12	0.16	0.14	0.14	0.12	0.20	0.16	0.16	0.13
Non-water material of the phantom wall	–	–	–	–	–	–	–	–	–	–	0.14	0.13	0.14	0.13
Combined uncertainty (%) ($k = 1$)	0.17	0.14	0.20	0.16	0.15	0.12	0.16	0.14	0.14	0.12	0.25	0.21	0.22	0.19

Table 9 – Experimental relative standard uncertainties in the chamber readings for the seven phantoms.

Source	Uncertainty (%)													
	DoseView 1D		WP1D		1D SCANNER		QWP-07		GRI-7632		PTW type 41023		QWP-04	
	6 MV	10 MV	6 MV	10 MV	6 MV	10 MV	6 MV	10 MV	6 MV	10 MV	6 MV	10 MV	6 MV	10 MV
Chamber reading (%) ($k = 1$)	0.14	0.13	0.12	0.11	0.11	0.09	0.15	0.12	0.13	0.08	0.18	0.16	0.11	0.11

phantoms for a vertical-beam geometry. The important components of the uncertainty were the window deformation and the non-water material of the window. Other publications have also referred to these components. Regarding the window deformation, TRS-398 and other authors have stated that the SSD and chamber depth may change owing to this effect.[2,14] Regarding the non-water material of the window, the uncertainty in the depth scaling of the window was considered to be 0.45 mm, as in McEwen et al.[15] When using the phantom, the user should understand these effects.

Comparing Tables 8 and 9, the uncertainties in the chamber readings obtained from the measurements (Table 9) were smaller than the estimated uncertainties (Table 8). Several components of the estimated uncertainties—namely, the movement distance from the origin to the reference depth, the analog scale, the air gap between the chamber wall and the waterproofing sleeve, the nonapplied correction attributable to the water density, and the non-water material of the phantom wall—would cause a constant shift in all of the ion chamber readings over the course of the measurements in Section 3.2. These components, therefore, did not likely contribute to the variation in each of the chamber readings. Since the major contribution to the values in Table 9 would be only attributable to the uncertainty in the users' techniques, there is a suggested difference between values in Tables 8 and 9.

Although the seven phantoms worked well as a water phantom for the calibration of the photon beam, achievement of the positioning uncertainty would be dependent on the user. Therefore, users need to pay attention to the major components of the positioning uncertainty corresponding to the phantom used in the clinic. The estimates presented are specific and applicable to the nineteen operators and seven phantoms used here. However, our work can be used by clinical physicists as a model for estimating the positioning uncertainty. It may also provide an idea about which components of the phantom are relevant for reducing the uncertainty.

6. Conclusions

We evaluated the positioning uncertainties for seven phantoms and the resulting uncertainties in the chamber readings. These uncertainties exhibited minor differences among the seven phantoms. The major components of these uncertainties were different among the 1D phantoms for a vertical-beam geometry, the phantom for a fixed waterproofing sleeve, and the 1D phantoms for a horizontal-beam geometry.

Conflict of interest

None declared.

Financial disclosure

None declared.

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